Assimilation of Coastal Radar Surface Current Measurements in Shelf Circulation Models

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LONG-TERM GOALS

To understand the fundamental issues involved with data assimilation in the coastal ocean and to use this knowledge to develop optimal, nowcast and forecast systems.

OBJECTIVES

The immediate scientific objectives of this research project are to develop practical, but still nearly optimal, methods for the assimilation of surface current measurements from land-based radar systems in coastal circulation models and to apply these methods to measurements from the Oregon shelf.

APPROACH

An array of SeaSonde HF radars has been deployed along the Oregon coast by P. M. Kosro of the College of Oceanic and Atmospheric Sciences, OSU. Data from a two-site HF array, which provides measurements of surface currents over a region about 50 km square, have been collected since November 1997. This project is aimed initially at developing and applying, in cooperation with Kosro, methods for the assimilation of these measurements in coastal circulation models.

The full primitive equations are sufficiently complicated that developing and testing nearly optimal data assimilation methods for use with them presents considerable difficulties. For this reason the data assimilation problem has been approached simultaneously from two directions; application of optimal variational inverse data assimilation schemes to simplified linear models and application of simplified, sub-optimal data assimilation schemes to a full primitive equation model.

Studies with a linear stratified model have been undertaken by the P.I.'s together with A. Kurapov to provide improved understanding of mathematical and physical issues associated with assimilation of surface current measurements. In initial efforts (Scott, 2000; Kurapov et al., 2001a,b) we worked with a simplified model widely used in previous theoretical studies of shelf circulation (e.g., Clarke and Brink, 1985). Although this model clearly has limitations, it includes representations of the essential physical effects of stratification, surface and bottom frictional processes, and shelf topography. Analytic results obtained for this model allow systematic examination of the sensitivity of errors in assimilation output products to errors in surface velocity measurements, wind stress, heat fluxes, initial conditions and boundary conditions. We are now focusing on a numerical inverse model for the linear

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3D stratified primitive equations, allowing for realistic shelf topography. Initial efforts involve a frequency domain model, which is being applied to studies of internal tides and being used to address fundamental questions about treatment of open boundary conditions in coastal data assimilation.

As a continuation of closely related research in the OSU NOPP project "The Prediction of Wind-Driven Coastal Circulation", the P.I.'s have also been working with P. Oke and P. M. Kosro on the development and application of a practical, sub-optimal data assimilation system (DAS) for implementation with the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987). A DAS based on the Physical Space Analysis System (PSAS; Cohn et al., 1998), has been developed for use in POM. As part of this effort, direct model simulations of flow on the Oregon shelf have been pursued with the objective of establishing dynamical rationalizations for the observed shelf flow.

WORK COMPLETED

Work with this linear stratified model has been extended to consider general time-dependent, three-dimensional flows, while still retaining idealized coastal geometry (Kurapov, et al., 2001a,b). Although this model is simplified, it contains a representation of the coastal-trapped wave dynamics that will be an important physical component of full primitive equation models with realistic topography. A generalized inverse has been developed and again progress with finding analytical solutions in terms of a sum of representer functions has been possible. In applications of coastal circulation models, there are typically considerable uncertainties in initial conditions and in open boundary conditions. The generalized inverse formulation here has been used specifically to investigate the effectiveness of surface data in restoring the state of the system at the initial time and at the open boundary. The linear model has also been utilized for statistical comparisons of the generalized inverse method (GIM) and two sequential methods, the Kalman filter (KF) and optimal interpolation (OI). The availability of analytical solutions for the representers allows straightforward calculations of the statistical functions required for the comparisons, and for studies of the consequences of incorrect prior assumptions about error statistics.

In our efforts with numerical methods applied to the linear primitive equations, a 3D stratified frequency domain inverse model has been developed and used for studies of internal tides on the central Oregon shelf. For tidal currents in a limited domain, such as the area covered by the HF radar systems on the central Oregon coast, an efficient solution method has been developed, based on direct factorization of the coefficient matrix for the second order elliptic system satisfied by the density perturbations. This approach provides solutions for both the forward and adjoint problems, and makes a variational generalized inverse method based on representer calculations straightforward. A modular structure has been maintained for numerical codes, allowing assimilation of various types of data (e.g., elevations, surface or subsurface currents), and flexibility in the choice of error covariances (e.g., allowing both strong and weak constraint data assimilation). Harmonic analysis of HF radar and ADCP currents for spring-summer 1998 has been performed in short time segments to account for intermittence and temporal variability of internal tides. Initial assimilation experiments have been performed with these data for a strong constraint model and the outputs have been validated by comparison to internal tides estimated from contemporaneous ADCP data.

For the studies utilizing POM, the model is applied to a limited-area high-resolution coastal domain for the central Oregon coast (Oke et al., 2001a,b,c). Realistic bottom topography for the Oregon shelf and slope is embedded in a large-scale periodic channel. The covariance fields needed for implementation of PSAS were calculated from an ensemble of runs, in which the model was forced with observed

winds from 17 "typical" summers (July and August) between 1969 and 1998. A time-distributed, sequential assimilation procedure that specifically addresses issues concerning primitive equation initialization and assimilation of low-pass filtered data was developed for use with the PSAS scheme. The effectiveness of this assimilation procedure has been demonstrated by assimilation experiments applied to CODAR data from summer 1998 and verified with subsurface current measurements (Oke, 2001a).

In addition, sixty-day simulations of the sub-inertial continental shelf circulation off Oregon were performed for a hindcast study of summer 1999. In Part 1 (Oke et al., 2001b), model results were compared with in situ currents, HF-radar derived surface currents and hydrographic measurements obtained from an array of moored instruments and field surveys and the model's sensitivity to initial stratification, surface forcing, domain size and river forcing were assessed. In Part II (Oke et al., 2001c), the modeled three-dimensional, time-varying circulation and dynamical balances were analyzed, providing a detailed synoptic description of the continental shelf circulation off Oregon for summer 1999.

RESULTS

For the three-dimensional, fully time-dependent linear problem (Kurapov et al., 2001a), the representer functions show interesting physical features concerning the zone of influence of each surface data point. The representer associated with uncertainty in the governing equation has a significant propagating component associated with the coastal-trapped wave dynamics present in the model. This clearly illustrates the non-local nature, in both time and alongshore coordinate, of surface data influence. Results from twin experiments give an explicit demonstration of the effectiveness of the inverse solution in restoring unknown initial conditions and across-shelf boundary conditions. In the comparisons of the GIM, KF and OI (Kurapov et al., 2001b), it is shown specifically how GIM can give relatively better results based on the use of future data. This improvement in performance can be explained in terms of wave dynamics. Derivation of the KF and OI schemes in terms of representers suggests approaches for improving the performance of practical OI schemes, based on combining time-lagged prior model covariances with the zero lag model covariances we have used in our implementation of the PSAS scheme.

Frequency domain representers for surface currents, which show the zone of influence of such data, have been obtained for a 3D stratified model with realistic topography (Figure 1a). Since the M2 frequency is superinertial, the representer is intensified along beams originating at the observation location or at bathymetric features (e.g., Stonewall bank in Figure 1). Inversion of HF radar data for the internal M2 tide off Newport (OR) have been performed for a series of one week time segments during the summer of 1998. The prior model was forced with depth-averaged currents from a barotropic tidal inverse model (Egbert and Erofeeva, 2001a,b); baroclinic open boundary velocities were then restored by the data assimilation. An example result of the prior and inverse solutions, along with depth dependant harmonic constituents estimated from the ADCP mooring, are given in Figure 1b. The computational domain is relatively small (39x57 km) and very little baroclinic signal is generated inside the domain by the barotropic forcing at the boundary. Data assimilation corrects the open boundary fluxes and thus improves the amplitude and phase of the tidal solution at the ADCP location throughout the water column.

In the data assimilation studies utilizing POM, the effectiveness of a practical assimilation scheme based on PSAS has been demonstrated through assimilation experiments applied to CODAR data from

summer 1998 (Oke et al., 2001a). Correlations between depth-averaged velocities calculated from ADCP data with those obtained from model-only and assimilation experiments are 0.42 and 0.78 respectively, showing marked improvement with assimilation of surface currents. Analysis of term balances in the assimilation output suggests that uncertainties in the wind forcing are a primary source of model error.

In the modeling studies utilizing POM, model outputs compared favorably with in situ currents and hydrographic measurements obtained from HF radar systems, moored instruments and field surveys (Oke et al., 2001b). Correlations between observed and modeled alongshore currents and temperatures in water depths of 50 m are in excess of 0.8 (Figure 2). In Part II (Oke et al., 2001c), the modeled three-dimensional time-varying circulation and dynamical balances are analyzed. The circulation is clearly wind-driven and strongly influenced by the alongshore variations in shelf topography. In the region of the coast where the alongshore topographic variability is small, the upwelling circulation is consistent with standard conceptual models for two-dimensional across-shore circulation. In the regions where topographic variations are greater, the circulation is highly three-dimensional. Over Heceta Bank the upwelling circulation is complicated, with weaker direct coupling to the wind forcing over most of the shelf. It is demonstrated that the upwelled water that is found over the mid-shelf off Newport is upwelled to the north and is advected to the south. Additionally, upwelled water over Heceta Bank is drawn from a different location to the south. The dynamical balances over the inner-shelf are divided into two regimes; in the coastal jet and inshore of the coastal jet. In the coastal, jet the tendency of the alongshore depth-averaged velocity V_t is large and is driven by the difference between the surface and bottom stresses during upwelling. Inshore of the coastal jet, V_t is small and is driven by the difference between the surface stress and a negative alongshore pressure gradient during upwelling. When the wind stress becomes small after upwelling, V_t is primarily balanced by the negative alongshore pressure gradient and a northward flow is generated. A region to the south of Newport over the inner-shelf is identified as the region where the northward momentum is initially generated.

IMPACT/APPLICATIONS

The studies with variational inverse schemes applied to linear models have begun to answer some of the basic questions associated with the assimilation of surface current measurements in coastal circulation models. In particular, these questions concern the extent of surface data influence on the flow at depth, the capability to retrieve unknown initial and boundary conditions, and the dependence of the inverse solution on assumed model and data error weights. Results obtained with the stratified inverse model prove that surface currents from HF radars contain information about internal super-inertial tidal flows at depth. The data assimilation studies with POM have produced promising results regarding assimilation of coastal radar surface current measurements in a full primitive equation model utilizing a practical data assimilation scheme. The modeling studies with POM provide new information about the three-dimensional, time varying circulation and the dynamical balances on the Oregon shelf, along with quantitative information regarding circulation modeling capabilities for this environment.

TRANSITIONS

RELATED PROJECTS

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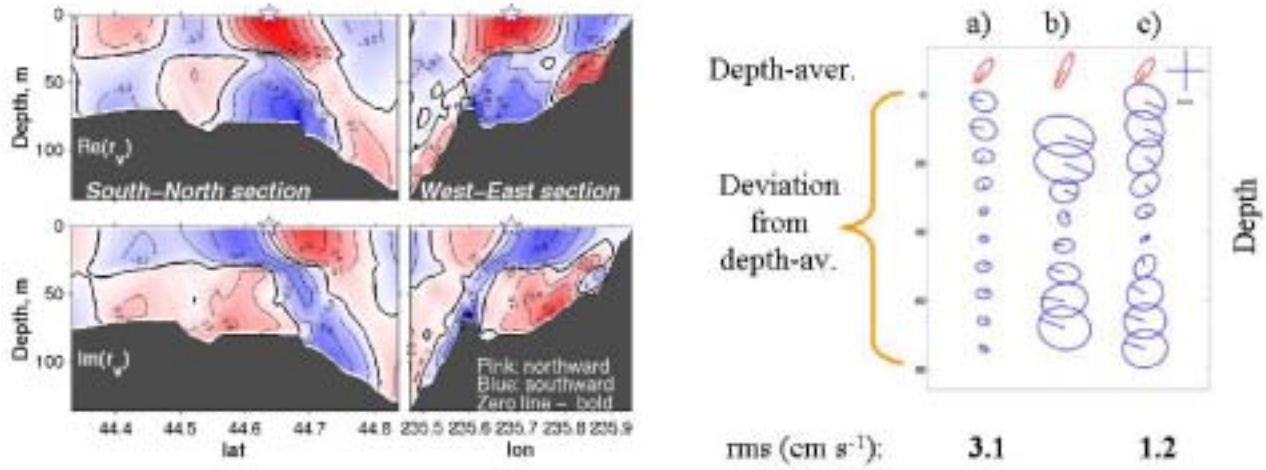
Figure 1. Left: The representer r_v showing the zone of influence of the surface alongshore velocity measurement on the modeled M_2 tidal alongshore current off central Oregon. The star shows the observation location. Right: Tidal ellipses at the ADCP location: a) model only solution forced by depth-averaged currents, b) ADCP data, c) inverse solution. Numbers under the plot show the rms difference of the solutions and the ADCP data.
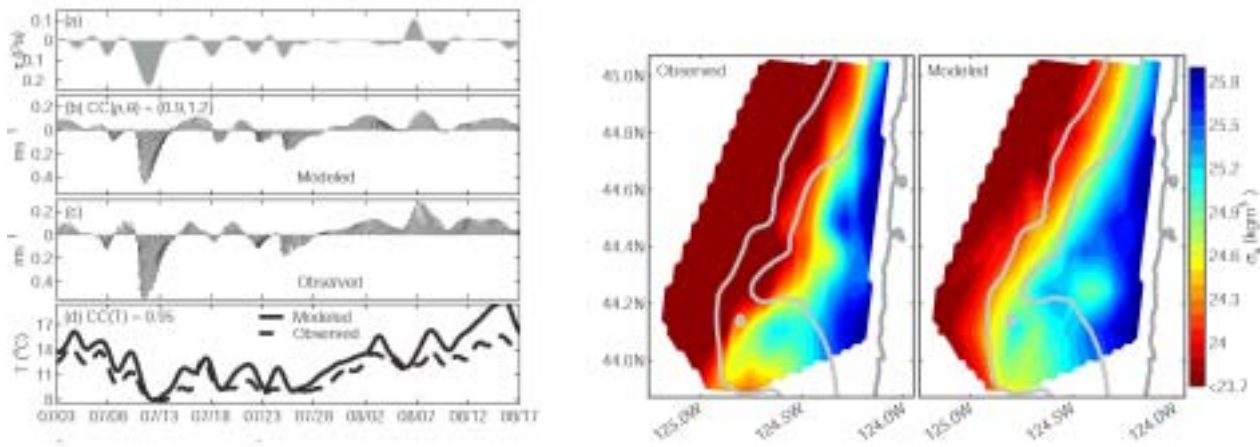

Figure 2. Left: (a) Alongshore wind stress τ, (b), (c) and (d) modeled and observed depth-averaged current vectors (U,V) and near-surface temperature T, from a mooring at 50 m depth off Newport OR during 1999. CC (ρ,θ)) is the amplitude and phase of the complex cross-correlation and C(T) is the cross-correlation between modeled and observed fields. The maximum cross-correlation between alongshore V and τ is 0.86. Right: Modeled and observed surface density between 7/23 and 7/26; the 100 and 200 m isobaths are gray (adapted from Oke et al., 2001b).